Four-fermion production and limits on anomalous couplings at LEP-2

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Abstract

Electroweak processes with four fermions in the final state were measured extensively at LEP-2 in e+e- collisions with centre-of-mass energies up to 209 GeV. By combining the results obtained by Aleph, Delphi, L3 and Opal, the predictions from the Standard Model were probed at the level of their present accuracy. An important outcome was the possibility to measure the predicted charged triple gauge boson self-couplings with a precision of a few percent. Moreover studies of four-fermion processes allowed new physics to be searched for by looking for anomalous gauge boson self-couplings. The measurements reported are also relevant to direct searches for new particles at LEP, as four-fermion processes contribute an important background in several cases. The latest results from the LEP experiments - some of which are now available in finalized form - and their combination are reviewed and discussed.

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1 Introduction

During the second part of the LEP program in 1995-2000, the centre-of-mass energy of the e^+e^- collisions was raised above the Z boson mass, reaching up to 209 GeV in the last year of operation. Integrated luminosities of about 700 pb^{-1} were collected by each of the four LEP collaborations ALEPH, DELPHI, L3 and OPAL, mostly above the W and Z-pair production thresholds. This allowed a comprehensive measurement program of boson pair production in e^+e^- collisions and more generally of all possible four-fermion ($4f$) final states. Two of the principal aims of LEP, directly validating the non-Abelian gauge structure of the standard model (SM) and searching for anomalous gauge boson self-couplings to reveal new physics beyond the SM (NP), could be pursued.

Most of the measured $4f$ final states result from processes seen at LEP for the first time. Initially some of the theoretical predictions and modelling were crude. Improvements were needed to match the experimental accuracy and were challenging, especially in the case of W-pair production[1]. The LEP measurements stimulated important work to compute radiative corrections and to devise appropriate ways to choose the scales of coupling constants when several were involved. The results were also included in practical event generators, where numerical divergences resulting from the small electron mass and the handling of the full set of graphs both had to be dealt with efficiently.

The experience gained at LEP in measuring $4f$ final states and the progress in the theoretical description and modelling were also important in the context of many new particle searches. In several cases the experimental signatures are very similar to those of the signal searched for, thus providing a useful environment to test the corresponding analysis techniques[1]. In the longer term, the improvements in the calculations will also benefit similar work at a future e^+e^- linear collider, where very high precision will be needed.

This report has two sections. Firstly, the latest measurements of $4f$ final states arising via the production processes $e^+e^- \rightarrow$ WW, ZZ, $Z\gamma^*$, eeZ/γ^* and $e\nu W$ are described. Secondly, interpretations of these measurements in terms of constraints on gauge boson self-couplings are presented, covering both charged and neutral triple gauge couplings (TGC) and the more recently studied quartic gauge couplings (QGC). For each channel, salient experimental, technical or theoretical features are highlighted and results from combining the LEP data-sets are presented when available. The main achievements are assessed after each section, comparing cross-section measurements to present theoretical predictions, and constraints on gauge boson self-couplings to estimates of effects in scenarios for NP, and to sensitivities expected in the future. A general conclusion is given with prospects to finalize and publish all results.

[1]A good example is the Z-pair production process, for which event rates and topologies were almost identical to those in the Higgs boson search.

2 Four-fermion processes

2.1 Signal definition in the simulation

The expected cross-sections of the production processes $e^+e^- \to$ WW, ZZ, $Z\gamma^*$, eeZ/γ^* and eνW are shown for illustration in fig.1. When combining the measurements of different sub-channels or experiments, it is important to establish common conventions. Two ways of defining a signal to be measured were used, either as the total cross-section in a kinematic region where it is dominant or as that corresponding exclusively to the relevant Feynman graphs. In both cases a sub-set of events was pre-selected in the simulation with high purity and efficiency in terms of relative contribution of the studied process. The selected rates were then scaled into those of the studied process, taking into account interference effects for identical final states. In the first method cuts were chosen in view of theory uncertainties affecting both the studied and other contributing processes in the different regions.

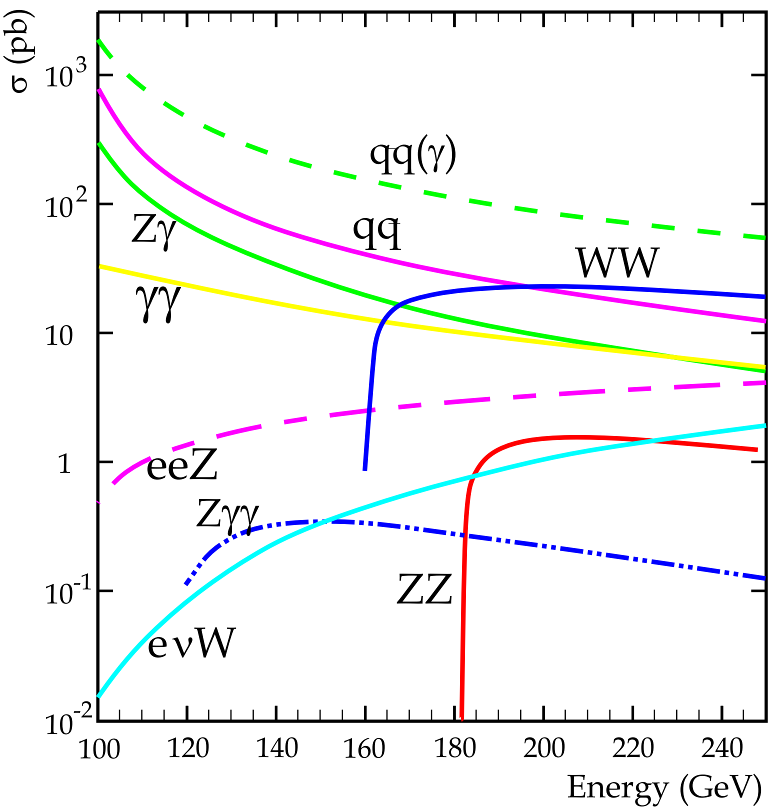

Figure 1: *Cross-sections of the main two and four-fermion processes at LEP-2.*

2.2 WW production

W-boson pairs are produced via the doubly-resonant graphs shown in fig.2 at tree level. Measurements of cross-sections and decay branching ratios, using a total of about 40000 events selected by the four LEP collaborations in the data collected in 1996-2000, are reported in[2]. All decay topologies $q\bar{q}q\bar{q}$, $l\nu q\bar{q}$ and $l\nu l\bar{\nu}$ were analysed. The separation achieved by ALEPH between signal and background is illustrated in fig.3.

The cross-sections obtained by combining all LEP results are shown in fig.4 as a function of the centre-of-mass energy, with a comparison to theoretical expectations[3]. The results clearly favour the SM prediction where the graphs in fig.2 involving TGCs are included, hence providing strong evidence for the non-Abelian gauge group structure of the theory. The highest precision was achieved by combining the results from all energies normalised to respective expectations. The best agreement was obtained using the new YFSWW[4] and RacoonWW[5] predictions. In these two calculations all $O(\alpha)$ electroweak (EW) radiative corrections relevant to the graphs in fig.2 were included through expansions about the W-pole (in the so-called leading and double pole approximations, respectively). They were introduced into "complete" $4f$ generators such as KoralW[6] and Wphact[7] by reweighting the relevant matrix elements, to achieve a consistent description of all processes in the full phase space[2]. The result obtained using YFSWW and combining the data from all energies was

$$\frac{\sigma_{\rm WW}}{\sigma_{\rm YFSWW}} = 0.997 \pm 0.007(stat) \pm 0.009(syst). \quad (1)$$

Results with RacoonWW differed by only 0.2%, well within the estimated theory uncertainty of 0.5%. On the contrary a set of previously used predictions which did not include all EW radiative corrections were too high by 2%, illustrating the sensitivity to loop effects achieved in these results[1].

The main source of uncertainty was from limited precision in the modelling of QCD fragmentation and hadronization, which could bias selection efficiencies in the semi-leptonic and fully hadronic sub-channels and in the latter, background levels from $q\bar{q}(\gamma)$ final states with four or more jets. Such effects being correlated among experiments and energies and of similar magnitude as the statistical errors, a careful treatment was important in the combination[3]. All systematic errors were grouped in four classes (100% correlated or uncorrelated among experiments or energies) and the full covariance matrix for the measurements at each experiment and energy was built for the χ^2-minimisation. This procedure was applied to all LEP cross-section combinations described in this report. For the result quoted in eq.1 it gave $\chi^2 = 35.4$ for 31 degrees of freedom.

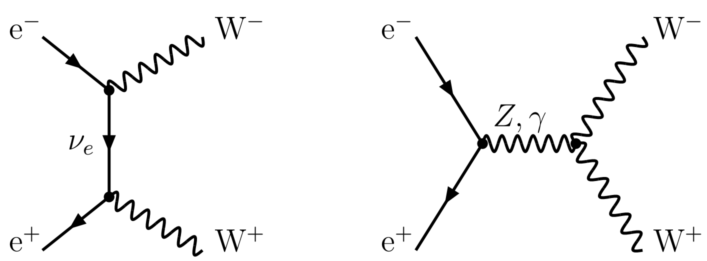

Figure 2: *Feynman graphs for on-shell WW production.*

[2]The matching to the two-photon generation was also studied in Wphact.

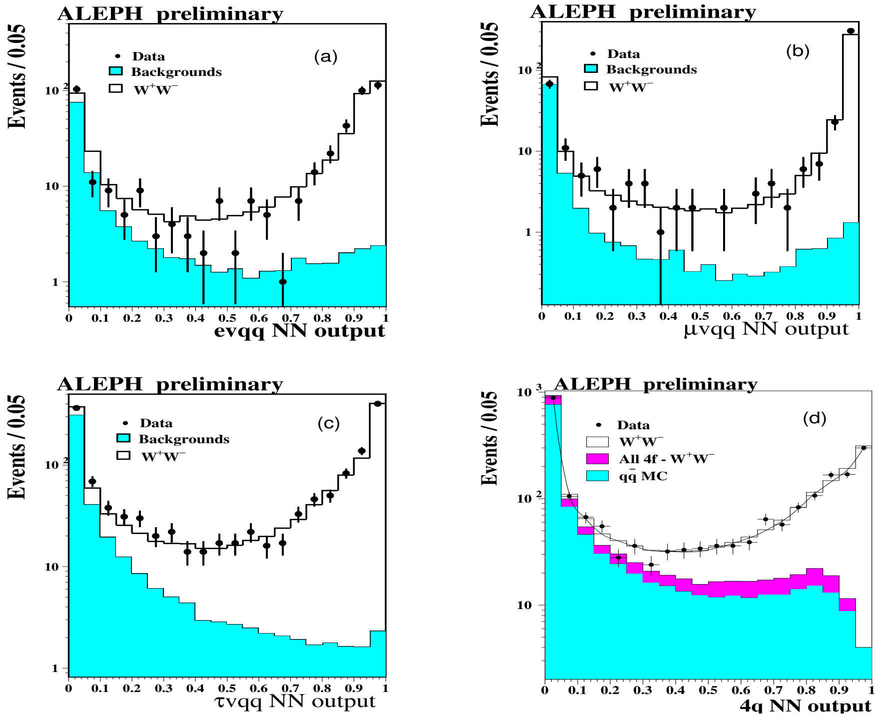

Figure 3: *Outputs from the neural networks used to isolate the W-boson pair signal in the fully hadronic and in the three semi-leptonic sub-channels.*

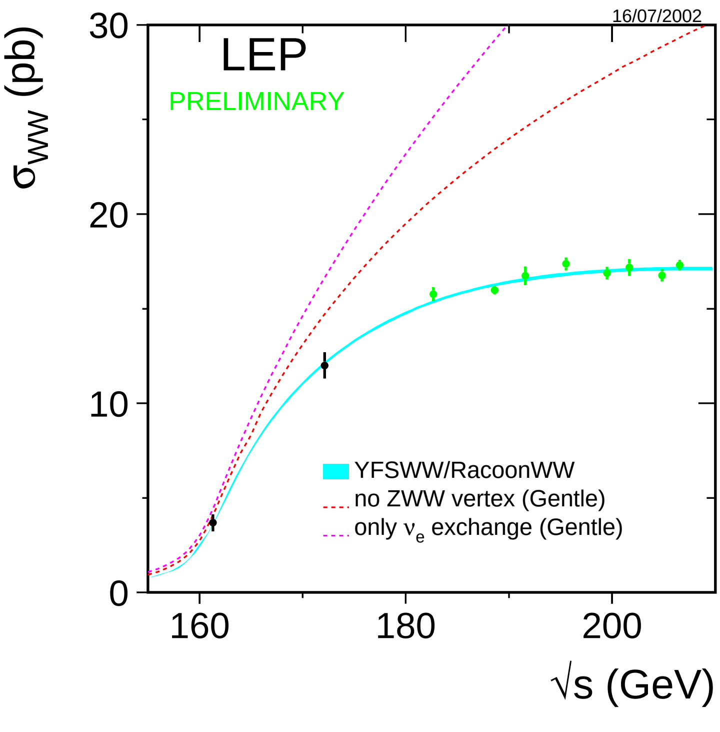

Figure 4: *Combined WW cross-section measurements compared with the SM predictions from YFSWW and RacoonWW. The dashed curves correspond to removing one or both of the graphs with triple gauge boson couplings in fig.2.*

2.3 ZZ production

Z-boson pair production occurs at tree level in the SM only via graphs with a t-channel electron (similar to that with a ν in fig.2). The cross-section was measured by the four LEP collaborations with data collected in 1997-2000 using all visible decays $q\bar{q}q\bar{q}$, $\nu\bar{\nu}q\bar{q}$, $llq\bar{q}$, llll and $\nu\bar{\nu}ll$[8]. The combined result[3] shown in fig.5 agrees well with the SM predictions[1]. Combining all energies gave

$$\frac{\sigma_{ZZ}}{\sigma_{ZZTO}} = 0.969 \pm 0.047(stat) \pm 0.028(syst), \tag{2}$$

using ZZTO, one of the calculations. The theoretical uncertainty, estimated to be 2%, was higher than for W-pairs (because radiative corrections were not fully included) but sufficient given measurement errors. The main correlated systematic errors, arising from the background modelling, were smaller than the statistical ones.

This measurement constrained potential anomalous production from NP, as described in sec.3.3 in the case of potential neutral TGCs. The reconstruction of the Z-boson polar angle achieved by DELPHI in this context is shown in the lower plot of fig.13.

Reconstructing the Z-boson pairs at LEP-2 was also an important test for the Higgs searches, since the analysed topologies were quasi-identical and cross-sections similarly small. L3 measured the ZZ $\rightarrow b\bar{b}X$ cross-section specially with this in mind[9].

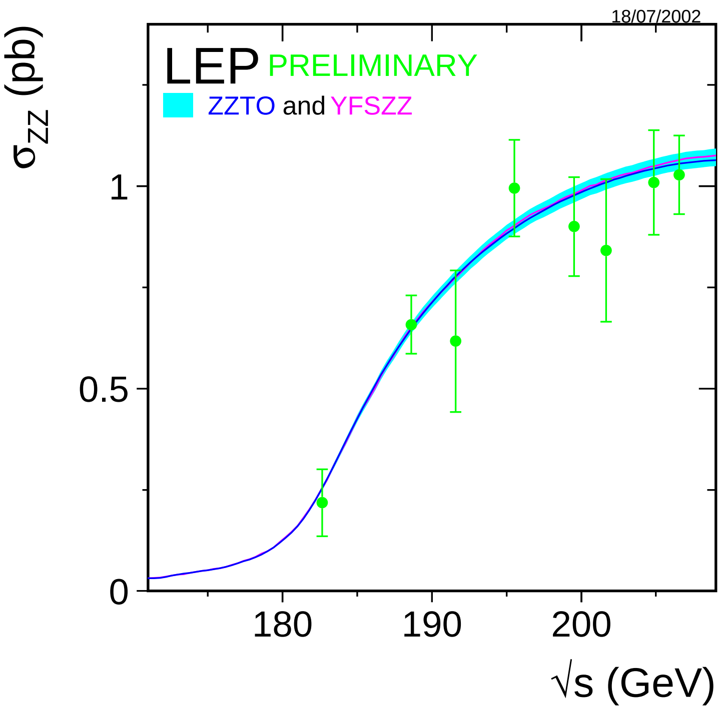

Figure 5: *Combined ZZ cross-section measurements compared with the SM predictions from ZZTO and YFSZZ. The band shows the theory uncertainty.*

2.4 Zγ^* production

Measurements of neutral boson pairs were also extended to include an off-shell photon intead of a Z. The process can then be described as a "virtual radiative return to the Z", with characteristic forward-peaked production and quasi mono-energetic γ^* at the lower masses. Resulting topologies are distinctive and gave sizeable backgrounds in several searches for NP, which needed checking. They also led to an original search for anomalous production via neutral TGCs, using a new parametrization extended to include off-shell terms (see sec.3.3).

DELPHI analysed the $\mu\mu q\bar{q}$, $ee q\bar{q}$, $\nu\bar{\nu}q\bar{q}$, llll and $q\bar{q}q\bar{q}$ final states and OPAL the $\mu\mu q\bar{q}$ and $ee q\bar{q}$ ones[10]. Good agreement was found. Fig.6 shows the di-quark and di-lepton mass spectra obtained by OPAL. The suppression at low di-quark mass comes from the smaller leptonic Z-boson decay branching ratio. In final states with electrons, t-channel single-boson processes ee(Z/γ^*) with both electron seen (see sec.2.5) enhanced the cross-section at high and low di-electron mass.

Another interesting final state, $\nu\bar{\nu}q\bar{q}$ has a mono-jet topology because the γ^* mass distribution peaks at low values. The corresponding energy-averaged cross-section was measured by DELPHI

$$\sigma_{Z\gamma^* \to \nu\bar{\nu}q\bar{q}} = 0.129 \pm 0.035(stat) \pm 0.015(syst) \text{ pb.} \tag{3}$$

The expected value was 0.088 pb. Uncertainties in the hadronization at low $q\bar{q}$ mass and in the way to set α_{em} given the different scales involved were shown to affect predictions by up to 5%[11]. Effects can be reduced by carefully treating the t-channel component in final states with electrons, and via phase space cuts. This should be good enough for the partial combination of three LEP experiments now planned.

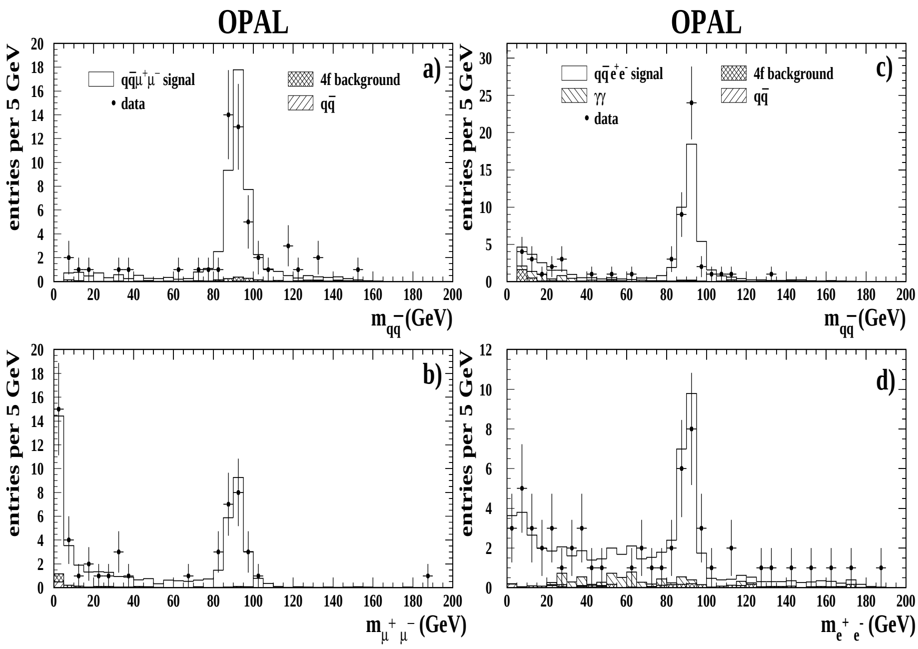

Figure 6: *Di-fermion invariant masses obtained in the* Zγ^* $\rightarrow$ ll$q\bar{q}$ *sub-channel after kinematic fitting with constraints from four-momentum conservation.*

2.5 eeZ/γ^* production

Neutral bosons can be produced singly via the so-called EW Compton scattering process $e^+\gamma \rightarrow e^+\gamma^*/Z$, where a quasi-real photon radiated from one of the beam electrons scatters off the opposite one (see fig.7). The signature of such events is an electron in the detector with moderate energy recoiling against the γ^*/Z system, with the other "spectator" electron mostly lost in the beam-pipe. LEP collaborations measured the $ee q\bar{q}$ and $ee\mu\mu$ final states with one electron lost using data collected in 1997-2000[12]. Competing "single-tag" contributions from two-photon processes were suppressed using correlations between the tag electron charge and direction. The reconstruction of single-Z or γ^* components is illustrated in fig.8, where the hadronic mass spectrum from DELPHI is shown. The excess of data below the Z-boson mass is assumed to come from biases in the two-photon background. A combination of cross-sections using the ALEPH, DELPHI and L3 results[3] was performed in the high mass single-Z region, giving good agreement with expectations. The signal was defined as the cross-section from all graphs in the kinematic region: $m_{f\bar{f}} > 60$ GeV/c^2 (f = q, μ), $12^\circ < \theta_{e^-} < 120^\circ$, $\theta_{e^+} < 12^\circ$, $E_{e^-} > 3$ GeV/c^2 (with implicit charge conjugation). Averaging over energies gave

$$\frac{\sigma_{\mathrm{Zee}}}{\sigma_{\mathrm{WPHACT}}} = 0.951 \pm 0.068(stat) \pm 0.048(syst), \tag{4}$$

using WPHACT, one of the calculations. Uncertainties in the way to set α_{em} and from treating initial state radiation given the different scales involved affected the predictions at the 5% level[11]. This matched the experimental errors, though some differential effects may need to be included.

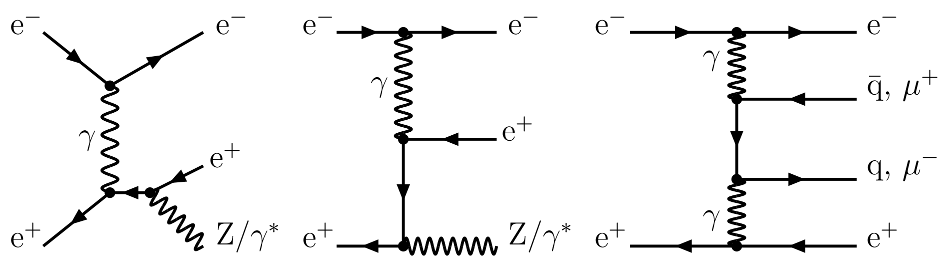

Figure 7: *Examples of tree level Feynman graphs for single neutral boson production (left and middle) and for the competing two-photon process (right).*

2.6 eν_eW production

W-bosons can also be produced singly via EW Compton scattering processes $e^+\gamma \rightarrow \bar{\nu}_e W^+$ as depicted in fig.9. The middle graph involves charged TGCs which can be probed measuring this process (see sec.3.2). As for single Z-boson production, the spectator electron is mostly lost in the beam-pipe.

LEP collaborations measured all the possible final states $e\nu_e q\bar{q}$, $e\nu_e l\nu_l$ ($l = e, \mu, \tau$) with the electron lost using data collected in 1997-2000[13]. The main signature was the large missing energy and either a pair of acoplanar jets with mass close to m_W or a

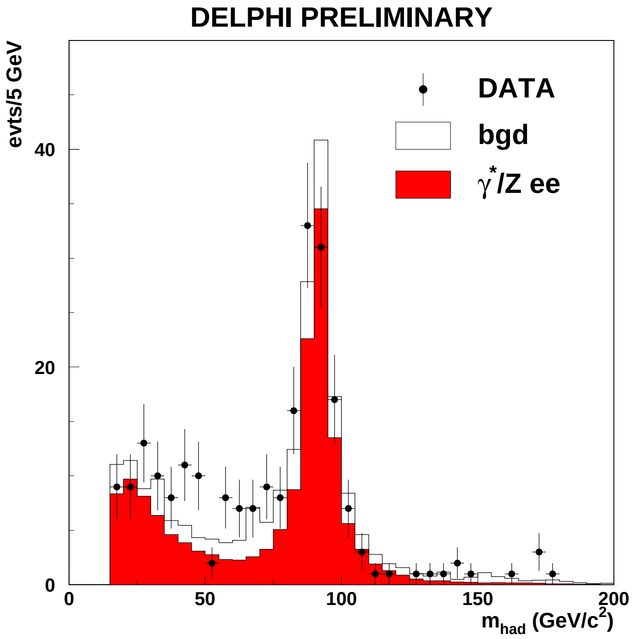

Figure 8: *Hadronic invariant mass obtained in the reconstruction of the* eeZ$/\gamma^*$ *process after kinematic fitting with constraints from four-momentum conservation and assuming an electron lost along the beam-line.*

single energetic lepton. The reconstruction achieved by L3 is illustrated in fig.10. The signal was defined as the complete t-channel sub-set of $4f$ graphs within kinematic cuts specified to reduce theoretically poorly known multiperipheral contributions from graphs such as the last one in fig.9: $\mathrm{e}\nu_\mathrm{e}\mathrm{q}\bar{\mathrm{q}}$: $m_{\mathrm{q}\bar{\mathrm{q}}} > 45$ GeV/c^2; $\mathrm{e}\nu_\mathrm{e}\mathrm{l}\nu_\mathrm{l}$ ($\mathrm{l} = \mu, \tau$): $E_\mathrm{l} > 20$ GeV; $\mathrm{e}\nu_\mathrm{e}\mathrm{e}\nu_\mathrm{e}$: $|\cos\theta_{\mathrm{e}^+}| < 0.95$ and $E_\mathrm{e}^+ > 20$ GeV. All results[3] agreed with SM expectations[1]. Combining the cross-sections measured by all experiments at all energies gave

$$\frac{\sigma_{\mathrm{e}\nu_\mathrm{e}\mathrm{W}}}{\sigma_{\mathrm{GRACE}}} = 0.949 \pm 0.067(stat) \pm 0.040(syst), \tag{5}$$

using GRACE, one of the calculations. Uncertainties similar to those described in sec.2.5 for single Z-bosons affected single W-bosons. Even though for the (gauge-invariant) t-channel graphs defining the single W-boson signal, complete fermionic one-loop corrections exist[14], allowing the correct scale for α_{em} to be set, a 5% error was estimated[1], also here matching the experimental precision.

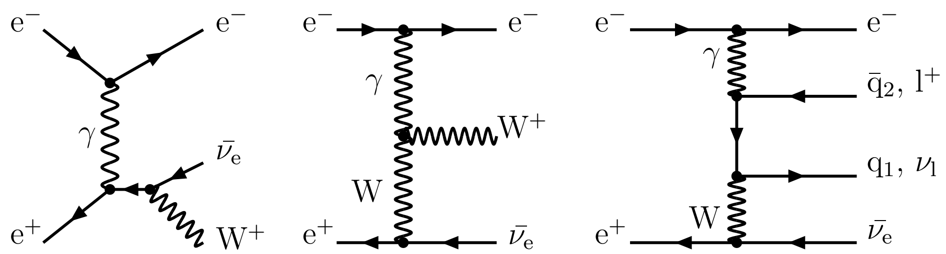

Figure 9: *Examples of tree level Feynman graphs for single W-boson production (left and middle) and for the multiperipheral contribution (right).*

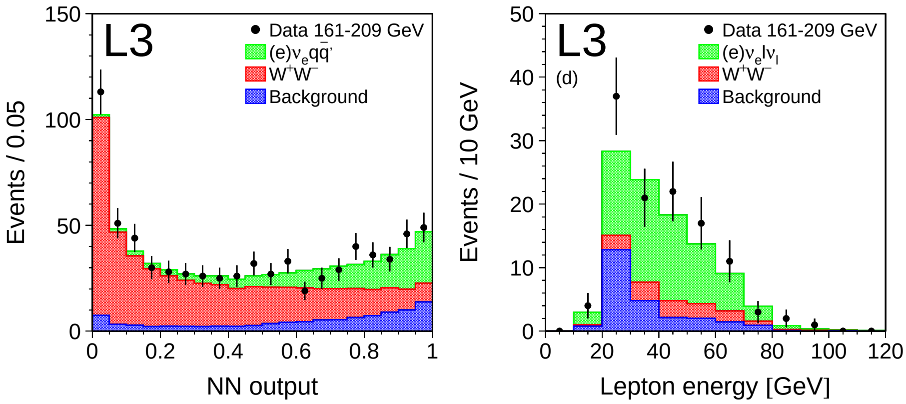

Figure 10: *Output from the neural network used to isolate the single W-boson signal in the hadronic sub-channel (left) and combined reconstructed lepton energy spectrum in the fully leptonic sub-channel (right).*

2.7 Summary

The comprehensive $4f$ measurement program conducted at LEP has been a success. It provided a large set of original results and established experimentally the SM environment where NP searches were carried out. The experimental precision achieved was matched by the accuracy of theory, as recalled in tab.1, in some cases after substantial work by the theoretical community[1].

In the case of the W-pairs the non-Abelian gauge group structure of the SM was clearly confirmed. The accuracy obtained, close to 0.5%, even allowed the SM calculation at loop level to be probed. In the case of the Z-pairs, a valuable experimental cross-check of the Higgs search at LEP-2 was made. In the case of the single-resonant boson processes SM predictions were tested in several yet unexplored regions.

Not all topics covered by the $4f$ sub-group of the LEP EW working group or by individual experiments could be reviewed in this report, for instance the measurements of the production polar angle, decay branching ratios, polarisation and spin correlations in the W-boson pair production process, and of the Z$\gamma\gamma$ cross-section[3].

Table 1: *Overview of experimental results and estimated theory errors for the production processes $e^+e^- \to WW$, ZZ, eeZ/γ^* and $e\nu W$. The predictions in the quoted ratios were obtained with the event generators YFSZZ, ZZTO, WPHACT and GRACE, respectively[1].*

physical process	measurement / prediction	theoretical precision
$\mathrm{e^+e^-} \to \mathrm{WW}$	$0.997 \pm 0.007(stat) \pm 0.009(syst)$	0.005
$\mathrm{e^+e^-} \to \mathrm{ZZ}$	$0.969 \pm 0.047(stat) \pm 0.028(syst)$	0.02
$\mathrm{e^+e^-} \to \mathrm{eeZ}/\gamma^*$	$0.951 \pm 0.068(stat) \pm 0.048(syst)$	0.05
$\mathrm{e^+e^-} \to \mathrm{e}\nu_\mathrm{e}\mathrm{W}$	$0.949 \pm 0.067(stat) \pm 0.040(syst)$	0.05

[3]A first partial combination of WWγ cross-section measurements is shown in fig.14 in the context of the search for QGCs described in sec.3.4.

3 Gauge boson self-couplings

3.1 Overview

Couplings between the SM gauge bosons were measured at LEP by analysing $4f$ (and other) final states. Deviations from tree level values are predicted in NP scenarios and arise also from radiative corrections. If large enough to be measured, such deviations can help to probe NP at energy scales beyond the kinematic range of direct searches for new particles.

Anomalous self-couplings were searched for at three and four boson vertices, involving both charged and neutral gauge bosons. Charged TGCs exist in the SM due to the non-Abelian gauge group structure (see sec.2.2). On the contrary neutral TGCs vanish at tree level. The SM predicts QGCs, but their size is very small. In the two latter cases one can only hope to detect anomalous contributions.

3.2 Charged triple gauge couplings

Parametrizations for the tree level VWW vertices (V=Z,γ) in the right and middle graphs of fig.2 and 9 involve in their most general form a Lorentz invariant Lagrangian with fourteen independent complex couplings[15]. Restricting the search to models with symmetries as in the SM (C, P, $U(1)_{em}$ and $SU(2)_L \times U(1)_Y$) the number of independent couplings reduces to three: g_1^Z, κ_γ and λ_γ. In the SM the two first couplings are equal to 1 and the latter vanishes. They can be related to the weak charge, magnetic dipole and electric quadrupole moments of the W-boson.

Deviations from the SM values can be probed in a complementary way via effects induced on the single and pair production processes (see sec.2.6 and 2.2), the former being sensitive mainly to κ_γ and the latter mainly to g_1^Z and λ_γ[4]. Results obtained by the four LEP collaborations using the data collected in 1996-2000 are reported in[17]. To maximize the sensitivity, the cross-sections, boson production polar angles, decay polar and azimuthal angles and average polarisation were exploited, using several adapted combination methods, based for example on "optimal observables"[19]. The reconstruction performed by L3 for the boson production and decay angles in semi-leptonic W-boson pairs is illustrated in fig.11.

The measurement of charged TGCs obtained by combining all LEP results is shown in fig.12[3] with the negative log likelihoods provided by each experiment for each coupling, and their sums. Each coupling was minimized independently with the two others kept at their SM values[5]. Good agreement with the tree-level SM expectations was found within errors of 2-5%.

The main source of correlated systematic uncertainty was of theoretical nature, from the recent inclusion of $O(\alpha)$ EW radiative corrections in the W-pair production process (see sec.2.2). This source of error was estimated conservatively as the full difference between results using Monte Carlo samples with and without these new corrections, yielding negative shifts of -0.015 for g_1^Z and λ_γ and -0.04 for κ_γ. Although these shifts are sizeable, it can be seen from their signs and from the values found for the couplings that the agreement with the SM is as good with or without them. This is different from the

[4] The $\nu\nu\gamma$ final state also has some sensitivity to κ_γ and λ_γ through the WW fusion process[16].

[5] Two and three-parameter analyses resulted in weak correlations.

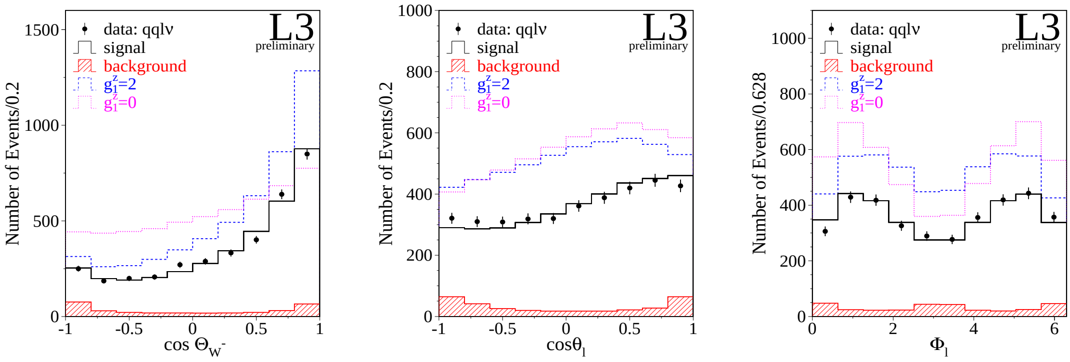

Figure 11: *Measured production polar angles (left), decay polar angles (middle) and decay azimuthal angles (right) of the W-bosons in the sub-channel* $\mathrm{WW} \rightarrow \mathrm{l}\nu\mathrm{q}\bar{\mathrm{q}}$*. The sensitivity to deviations from the SM prediction* $\mathrm{g}_1^\mathrm{Z} = 1$ *is indicated.*

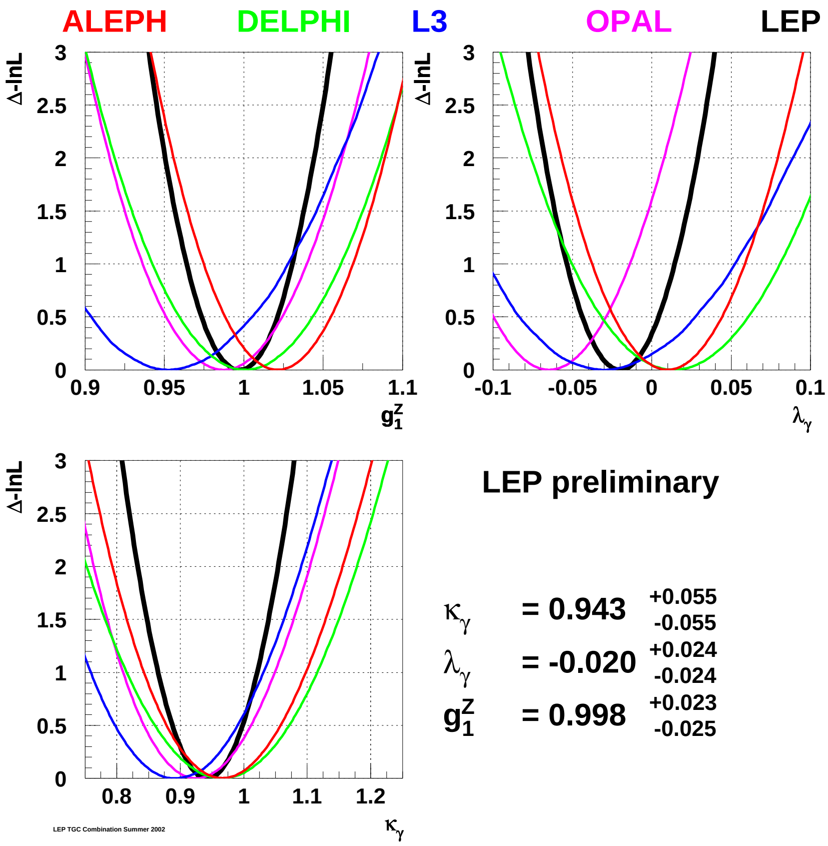

Figure 12: *Measurement of the charged TGC parameters* g_1^Z, κ_γ *and* λ_γ.

cross-section measurement, where the improvement from the new corrections was clear. This feature is perhaps a little surprising, since more information is used to extract the charged TGCs, like angles and the single W-boson channel.

Since these shifts had similar sizes as the statistical errors and were fully correlated between energies and experiments, a careful treatment was implemented in the combination, expressing the likelihoods as functions of each coupling and of additional free parameters, to represent each error weighted by its sensitivity in each experiment, and by then performing a simultaneous minimization[3].

3.3 Neutral triple gauge couplings

There are no self-couplings involving exclusively neutral gauge bosons at tree level in the SM.

For NP satisfying Lorentz invariance and preserving the $U(1)_{em}$ and Bose symmetries for identical particles, the most general parametrization for the ZZZ, ZZγ and Z$\gamma\gamma$ vertices has twelve independent parameters, six of which are CP-conserving: $h_{3,4}^{Z/\gamma}$ and $f_5^{Z/\gamma}$, while the other six are CP-violating: $h_{1,2}^{Z/\gamma}$ and $f_4^{Z/\gamma}$[15]. The h and f terms describe the VZγ and VZZ vertices, respectively, where $V = Z, \gamma$ is off-shell but the two other bosons are on-shell.

These two classes of neutral TGCs can be probed via effects induced on the production processes $e^+e^- \to Z\gamma$ and ZZ, respectively (see sec.2.3 for the measurement of the latter). Results obtained by the four LEP collaborations using the data collected in 1996-2000 are reported in[18]. The cross-sections and boson production angles were exploited, as well as, for the $e^+e^- \to Z\gamma \to q\bar{q}\gamma$ process the angle between the photon and nearest jet and, for the $e^+e^- \to Z\gamma \to \nu\bar{\nu}\gamma$ process the photon energy. The reconstruction performed by DELPHI for the two angles just described is illustrated in fig.13.

The constraints on neutral TGCs obtained combining all LEP results are shown in tab.2[3]. The precision was dominated by statistical errors. There was lower sensitivity to f than to h terms because of the less favourable kinematics at the threshold for Z-boson pair production.

Table 2: *Combined 95 % confidence level probability intervals for the neutral TGCs probed by measuring the* $e^+e^- \to Z\gamma$ *and ZZ processes. The constraints shown on h and f terms result from the single and two-parameter analyses, respectively. Some correlation between h terms was observed in a two-parameter analysis done combining results from three experiments[3]. The two latter bosons at each listed vertex correspond to the final state produced and are on-shell.*

vertex	CP	parameter	95 % CL limits
$\gamma Z\gamma$	odd	h_1^γ	[-0.056, +0.055]
$\gamma Z\gamma$	odd	h_2^γ	[-0.045, +0.025]
$\gamma Z\gamma$	even	h_3^γ	[-0.049, +0.008]
$\gamma Z\gamma$	even	h_4^γ	[-0.002, +0.034]
$ZZ\gamma$	odd	h_1^Z	[-0.13, +0.13]
$ZZ\gamma$	odd	h_2^Z	[-0.078, +0.071]
$ZZ\gamma$	even	h_3^Z	[-0.20, +0.07]
$ZZ\gamma$	even	h_4^Z	[-0.05, +0.12]
γZZ	odd	f_4^γ	[-0.17, +0.19]
ZZZ	odd	f_4^Z	[-0.30, +0.28]
γZZ	even	f_5^γ	[-0.34, +0.38]
ZZZ	even	f_5^Z	[-0.36, +0.38]

The analysis done treated h and f terms separately, though it has recently been shown that using the $SU(2)_L \times U(1)_Y$ symmetry as in the charged case relates the VZγ and VZZ vertices for some classes of operators and can lead to fewer independent couplings[20]. Although some generality may be lost, this will now be done as well. It is expected that

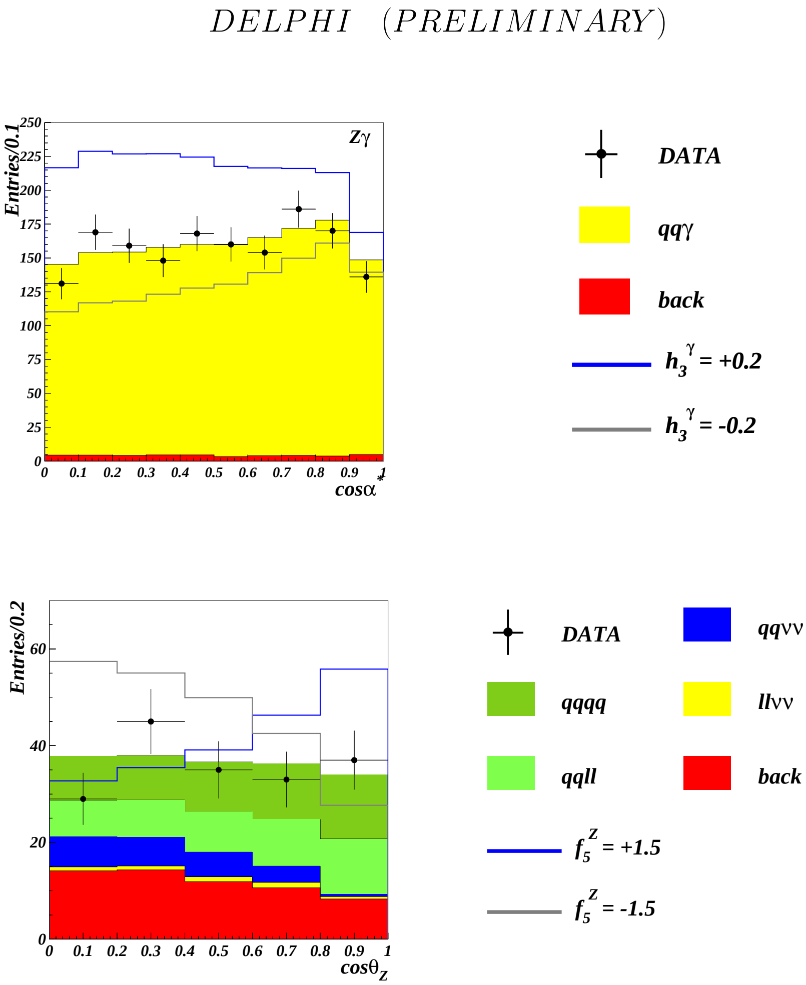

Figure 13: *Measured decay angle of the Z in its rest frame in the* $\mathrm{e^+e^-} \rightarrow \mathrm{Z}\gamma \rightarrow \mathrm{q\bar{q}}\gamma$ *process (upper plot). Measured production angle in Z-boson pairs for the main final states studied by DELPHI[8] (lower plot). The sensitivity to the presence of CP-conserving* h_3^γ *and* f_5^Z *couplings, respectively at the* $\gamma Z\gamma$ *and ZZZ vertices, is indicated.*

the more precise $\mathrm{e^+e^-} \rightarrow \mathrm{Z}\gamma$ measurements will dominate the constraints from such a combined analysis.

Another recent theoretical development has enabled a generalization of the description by including off-shell bosons[21]. It was argued that the resulting effects cannot be ignored in detailed experiments, especially if data measured outside the strictly on-shell regions of the Z-pair and Zγ processes are also used. A first study in this direction has been presented by DELPHI, based on the Zγ^* production measurement (see sec.2.4)[18].

3.4 Quartic gauge couplings

The couplings predicted in the SM at the WWWW, WWZZ, WW$\gamma\gamma$ and WWZγ vertices are below LEP-2 sensitivities. The searches performed probed potential anomalous contributions arising from NP, concentrating on operators which do not simultaneously cause anomalous TGCs. It has been argued that such operators, often referred to as “genuine” QGCs, can be related more directly to the scalar sector of the theory[22]. The parametrization used involves four CP-conserving terms at the WW$\gamma\gamma$ and ZZ$\gamma\gamma$ vertices, $a_{0,c}^{\mathrm{W,Z}}$, and a CP-violating one at the WWZγ vertex, a_n[23]. By convention these terms are usually normalised to Λ^2, the square of the energy scale at which the NP responsible for them appears.

Experimentally these terms were probed by measuring the three boson final state processes $\mathrm{e^+e^-} \to \mathrm{WW}\gamma$ (for $a_{0,c}^{\mathrm{W}}$ and a_n) and $\mathrm{e^+e^-} \to \mathrm{Z}\gamma\gamma$ (for $a_{0,c}^{\mathrm{Z}}$), using both the rates and energy spectra of the photons[24]. The presence of $a_{0,c}^{\mathrm{W,Z}}$ terms was also studied through their influence on the $\mathrm{e^+e^-} \to \nu\nu\gamma\gamma$ process, via a contributing graph with WW fusion and another one involving neutrino pair production mediated by a Z boson which radiates two photons[25]. Both the rate and the photon pair recoil mass spectrum were exploited.

Only the L3 Z$\gamma\gamma$ and OPAL $\nu\nu\gamma\gamma$ results were combined so far, allowing to set the following 95% CL limits on the ZZ$\gamma\gamma$ vertex: $-0.033 < a_0^{\mathrm{Z}} \times GeV^2/\Lambda^2 < 0.046$ and $-0.009 < a_c^{\mathrm{Z}} \times GeV^2/\Lambda^2 < 0.026$[3]. A combination of the cross-sections obtained by DELPHI and L3 for the WWγ final state was also performed[6] and is illustrated in fig.14, together with the SM prediction of EEWWG[26] and the sensitivity to the CP-violating a_n coupling. No combined constraints on $a_{0,c}^{\mathrm{W}}$ and a_n QGCs were yet obtained from this limited cross-section information, but individual results have been published, for example the L3 one: $-0.015 < a_0^{\mathrm{W}} \times GeV^2/\Lambda^2 < 0.015$ and $-0.048 < a_c^{\mathrm{W}} \times GeV^2/\Lambda^2 < 0.026$ (using also the information from the $\nu\nu\gamma\gamma$ final state), and $-0.14 < a_n \times GeV^2/\Lambda^2 < 0.13$.

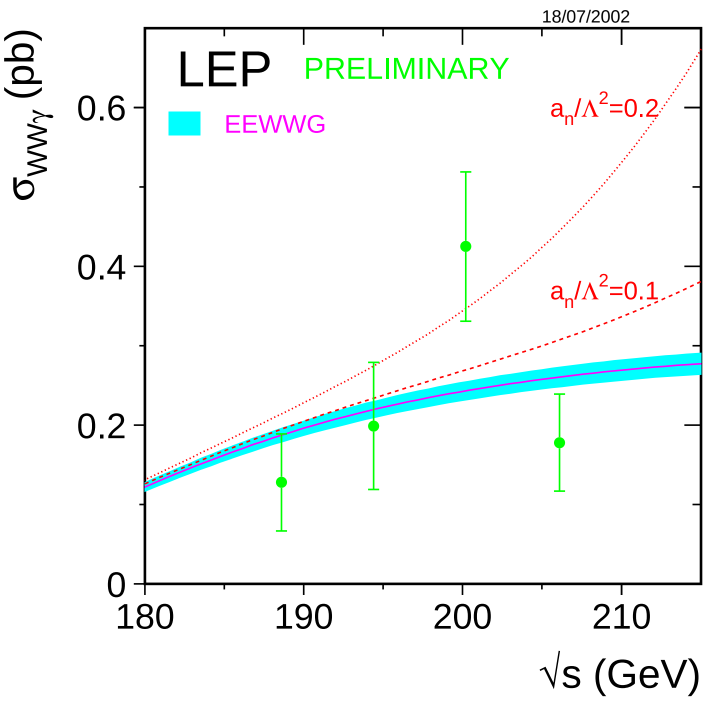

Figure 14: *Combination of WWγ cross-section measurements by DELPHI and L3 compared with the SM prediction. The sensitivity to the presence of a CP-violating a_n coupling at the WWZγ vertex is indicated by the predicted distribution for two values of a_n/Λ^2 (in units of GeV^{-2}).*

[6]The signal was defined as the cross-section from all graphs in the kinematic region: $|m_{\mathrm{f\bar{f}}} - m_{\mathrm{W}}| < 2\Gamma_{\mathrm{W}}$, $\cos\theta_{\gamma,\mathrm{f}} < 0.90$, $|\cos\theta_\gamma| < 0.95$ and $E_\gamma > 5$ GeV.

3.5 Summary

The charged TGCs were measured within a few 0.01 of their predicted values in the SM, confirming again the non-Abelian gauge group structure. NP giving anomalous contributions of the order of these errors could be excluded. The sensitivity was not enough to probe SM loop effects, which are predicted to be at the 0.003 level. It was also barely enough to sense effects from SUSY even in the most optimistic scenarios with sparticles not far above the kinematic limit. A Z′ with a low mass would on the other hand have produced visible effects, but would also have been strongly felt in di-fermion cross-section measurements[27].

Some improvement to the precision is still expected from on-going work to estimate the uncertainty on the $O(\alpha)$ corrections in a better way than just quoting their full effect, for instance by varying assumptions in the theoretical treatments used. This could help to understand why there was some sensitivity to SM loop effects when measuring the total cross-section (see sec.2.2) but not the charged TGCs (see sec.3.2). Further ahead experiments at higher energies will improve the sensitivity. The TeVatron with 10 fb^{-1} and the LHC with 300 fb^{-1} should for example pin down λ_γ to about ± 0.005 and ± 0.0003, respectively. A good sensitivity to all TGCs is expected at a future e^+e^- linear collider. For instance TESLA should reach a precision of a few ± 0.0001 after collecting 1500 fb^{-1} at $\sqrt{s} = 800$ GeV[28].

The neutral TGCs were found to be zero as expected, but within larger error ranging from ± 0.05 to ± 0.30. In the case of perturbative NP, anomalous contributions to neutral TGCs are expected to be depressed by at least one more power of $m^2_{\mathrm{W,Z}}/\Lambda^2$ compared to charged ones, because operators with higher dimension are involved. Neutral TGCs expected from several scenarios for NP have for example been studied in [29]. The overall conclusion reached was that potential effects were generally below experimental sensitivities, except in cases of new particles with masses just above the kinematic reach, or of NP which is not perturbative.

The QGCs were also found to be close to zero as expected. Here the expected "natural" size of couplings at LEP-2 is about 1 for NP with an energy scale $\Lambda = 3$ TeV, which is far below the experimental sensitivity[30].

Even though effects on gauge couplings from the NP scenarios that were investigated turned out to be too small to be detected, the systematic search program carried out at LEP-2 was certainly justified to demonstrate the validity of the SM, and to show that there is no evidence of new physics from totally unexpected sources. The analyses done are also a useful preparation for similar work at future high energy colliders.

Recent measurements and analyses of spin density matrix elements in the W-boson pair production process are not covered here.

4 Conclusions and prospects

The results on the measurements of $4f$ final states and gauge boson self-couplings are an important part of the LEP legacy. The present work is to complete the documentation promptly. while the main physicists involved are still available. All final experimental results and combinations are expected during 2003. At the time of this writing, only the measurements by DELPHI of Z-boson pair production, by L3 of single boson production and quartic couplings, and by OPAL of $Z\gamma^*$ production are considered truly “final” in the sense of being described in a refereed CERN-EP preprint note or journal publication. It is important to ensure a high quality and an appropriate level of detail in the descriptions of the analyses and final results to facilitate future reading.

5 Acknowledgements

The beautiful experimental results presented in this report are one of the cherries on the LEP-2 cake: a long chain of prior tasks was required. The accelerator physicists and operators achieved energies and luminosities in excess of expectations. The experimental teams took quality data with ever rising efficiencies. Alignment and calibration procedures were carried out. Huge sets of Monte Carlo simulations were produced and checked. And more... All this detailed work and the people involved must be recognised.

The work of the $4f$ and Gauge Couplings LEP working groups should also be acknowledged. Such common inter-collaboration groups provide a competitive and stimulating environment where the best experts from each experiments can share their knowledge, discuss approaches, compare and cross-scrutinize each others results and methods. They were an important ingredient which enhanced the scientific quality and can serve as example for the future.

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